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14. ABSTRACT
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15. SUBJECT TERMS
Ligurian Sea Air-Sea Interaction Experiment, atmospheric data assimilation, NCOM

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Air-Sea Interaction In The Ligurian Sea: Numerical Simulations And In-Situ Data In The Summer Of 2007.

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Abstract- **In situ experimental data and numerical model results are presented from the Ligurian Sea in the north-western Mediterranean. Here surface winds are light in summer except during occasional Mistral events which are often associated with cyclogenesis in the lee of the Alps. The Ligurian Sea Air-Sea Interaction Experiment (LASIE07) took place in June 2007, with a focus on the coincident measurement of oceanic and atmospheric boundary layer properties.**

To help interpret the observational results we use the Coupled Ocean-Atmosphere Mesoscale Prediction System (COAMPS®), developed at the Naval Research Laboratory. This system includes an atmospheric sigma coordinate, non-hydrostatic model, coupled to a hydrostatic sigma-z level ocean model (Naval Coastal Ocean Model), using the Earth System Modeling Framework (ESMF). Both models are at high resolution: the inner nest of the COAMPS domain is on a 4 km grid with 40 vertical levels, and that for NCOM on a 2km grid with 50 levels.

The coupled model system is evaluated for a month-long simulation which includes data assimilation in the atmosphere but not the ocean. Correlatation coefficients between model and observed values for near-surface wind speeds, and turbulent heat fluxes are above 0.5 (significant at 99%) at a deep water mooring.

A comparison of the coupled run with an uncoupled atmospheric run using analysis SST at the surface boundary, both of which use atmospheric data assimilation, does not reveal significant or systematic differences. Therefore a non-assimilating run for the period of a strong wind event (26-29 June), is performed to examine more closely the impact of coupling on the flux fields and SST. Here, the cooling of SST up to 3°C over 72 hours in a fully coupled run affects the surface stress, which is reduced by ~20%, and the surface latent heat flux which is reduced by 50%, relative to an uncoupled simulation where the SST is kept fixed at the initial value of the coupled run. In other words, the coupling provides a negative feedback on the surface forcing under strong winds.

I. Introduction

Meteorology

The meteorology of the Ligurian Sea is strongly influenced by the surrounding land masses, and in particular the mountain ranges of the Alps, Massif central and Pyrenees. Cyclogenesis occurs in the lee of the Alps all year round, with a strong seasonal cycle: it is most common in winter, but still occurs in summer, when the number of events is typically about half that which normally occurs in winter [1].

In the situation of a low centered in the Gulf Of Genoa, synoptic northerly flow impinges on the mountain ranges, and is funneled by the topography, leading to strong topographic jets, the northerly Mistral flowing between the Alps and Massif central and down the Rhine valley, the north-westerly Tramontane between the Massif Central and the Pyrenees (e.g. [2]).

In summer, the mean wind picture (Fig. 1, from QuikSCAT) shows the influence of the Mistral and Tramontane winds, with strong north-westerly winds emanating from the Gulf of Lions and turning cyclonically in the Ligurian Sea to south-westerly. Winds are weaker in the Gulf of Genoa and in the lee of the islands of Corsica and Sardinia, whereas a strong corner jet exists at the north-west tip of Corsica and there is a jet in the Strait of Bonifacio between the two islands.

Oceanography

The Ligurian Sea (Fig. 2 shows the mean SST and bathymetry of the Sea) comprises a relatively shallow region (500m or less) north-east of the island of Corsica, and deeper water (over 2000m) to the north-west. The summer climatology of SST (Fig. 2) shows the dominant influence of wind stress on SST distribution. Relatively cool SST is seen in the deep Ligurian Sea, and east of the Strait of Bonifacio, where winds are strong (Fig. 1). Warmer SST is found in the lee of the islands and in shallow water.

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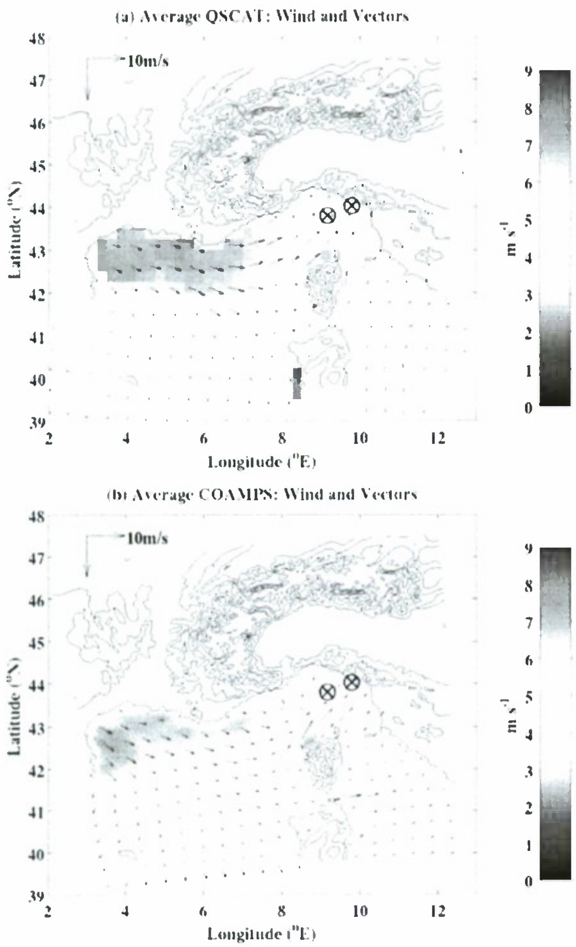

Figure 1. Near-surface winds over Ligurian Sea. (a): monthly average of neutral equivalent 10 m winds from QuiKSCAT. (b): monthly average of 10 m winds from COAMPS. Averaged from 10 June to 9th July 2007, using model data only at times of the QuikSCAT swath (6am, 6pm local time). The topography of the Alps and Massif Central is contoured. The location of the ODAS (offshore) and METEO (coastal) moorings are shown in circles.

Aims of the study

The aims of this study are twofold. First we wish to validate the coupled model against a detailed dataset of atmospheric and oceanic measurements. Secondly we will investigate the feedbacks from the ocean in synoptic events in summer in the Ligurian Sea, using fully coupled simulations and an uncoupled system where the atmospheric model receives no feedback from the ocean model. The paper is structured as follows. Section 2 introduces the experimental dataset and the coupled model. Section 3 validates the surface and near-surface variables, and the fluxes, from the model against the observations, for a one month period. Section 4 describes a three day case event of strong Mistral winds and determines the ocean feedback to the atmosphere. This is followed by conclusions.

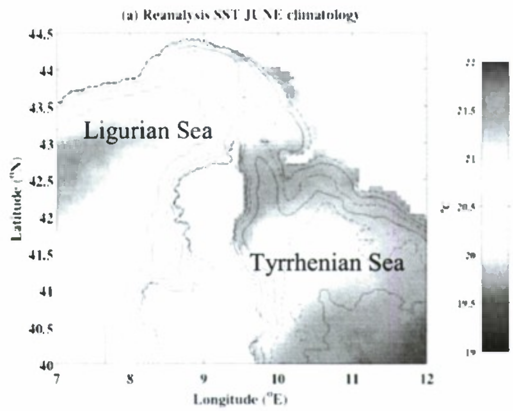

Figure 2. Climatological mean SST, and bathymetry, for the Ligurian and Tyrrhenian Sea for June. SST is got from the GOS CNR reanalysis products. Bathymetry is contoured at 2000m, 500m, 100m (solid) and 1000m, 200m, 50m (dash).

II. OBSERVATIONS AND MODELS

LASIE-07 experiment

A field experiment to study air-sea interaction processes in the Ligurian Sea (Fig. 1 shows mooring locations as crosses) took place in June 2007. An important aspect of the experiment was the gathering of concurrent atmospheric and oceanic soundings. The focus of the experiment was on the boundary layers, to provide a test-bed with which to evaluate coupled models and boundary layer parameterizations.

COAMPS Numerical Model

Numerical simulations are performed with the Coupled Ocean-Atmosphere Mesoscale Prediction System (COAMPS®), developed at the Naval Research Laboratory. The atmospheric component is a terrain-following sigma coordinate, non-hydrostatic model [3,4] There are three nests of horizontal spacing 36km, 12km and 4 km respectively each nest having 40 vertical layers (with 14 layers in the lowest 1000m, and four in the lowest 100m).

The ocean component is the hydrostatic Naval Coastal Ocean Model (NCOM), which uses a combination of terrain following sigma and z-level coordinates [5,6]. The model is based on the Princeton Ocean Model [7] and also includes a free surface (the sigma coordinates move up and down with the surface elevation). For this simulation, there are 35 sigma layers in the top 550m, and 15 z levels below that. The vertical resolution changes with depth such that in deep water (> 550m) there are typically 10 layers in the top 10m, and 24 in the top 100m, allowing for good resolution of upper ocean processes. (In shallower water, the resolution increases as dictated by the sigma coordinates.) The ocean model was set up with an outer and inner nest with 6km and 2km grid

Lateral boundary conditions for the atmospheric model come from the operational NOGAPS 1degree model, 6 hourly output, whilst those for the ocean model come 6 hourly from the global, data assimilating version of the NCOM, 1/8degree model [8].

The models are coupled using the Earth System Modeling Framework (ESMF). This enables the passing of variables between atmosphere and ocean in memory, and organizes horizontal interpolation between the fields in the different components. Time steps for the outer ocean and atmospheric grids are both 90 seconds and the coupling interval used in our simulations (12 minutes).. The ocean is rapidly updated with changes in the atmosphere, and vice-versa. The system runs using MPI.

The model is initialized on June 10th, 5 days before the main observation-model comparison begins. The reason for this short spin-up is that the ocean model has no data assimilation, and a longer spin-up would possibly allow a large drift away from observed conditions. (The initial ocean condition is taken from a data-assimilating run of the global NCOM.)

Satellite Data

Neutral wind vectors at 10 m [9] are derived from the SeaWinds QuikSCAT scatterometer, and obtained from the Remote Sensing Systems website (www.remss.com). The twice-daily (approximately 0600 Local Time and 1800 Local Time) data is mapped onto a regular Cartesian ¼ degree grid.

We use an optimal interpolation of infrared satellite SST provided by CNR, GOS [10]. This product utilizes AVHRR and other infrared satellite data gathered during nighttime, when the expected differences with in-situ bulk SST are expected to be at a minimum.

Model Experiments

Two main experiments are performed for this study. The first is a fully coupled run using the model as described above. For the second experiment, we run the atmosphere and ocean components, but the SST from the ocean is not passed to the atmosphere. Instead the atmospheric model uses SST from an analysis of observations to compute the bulk fluxes. These fluxes are then used within the atmosphere and ocean model. We refer to this as the 'Uncoupled run', wherein the ocean is forced by the atmospheric component, but there is no feedback from ocean to atmosphere.

III. SURFACE FLUX TIMESERIES

Here we compare measurements of near-surface variables from the ODAS and METEO moorings, and estimates of surface fluxes at ODAS, with the COAMPS model in a coupled and uncoupled mode. The fluxes for the COAMPS model are computed within the model, as described above, using ocean model SST (coupled case) or NCODA SST (uncoupled case) and atmospheric near-surface variables, using the modified Louis scheme [11]. For the ODAS mooring, we estimate fluxes from the wind measurements at 14.5m and temperature and humidity at 13m, using the Fairall et al. 1996 algorithm.

Wind speeds during LASIE07 trial

Typically, wind speeds in the LASIE07 trial area were light, with a monthly average about 4-5ms^{-1} (Fig. 1a). Stronger winds were observed emanating from the Gulf of Lyons (Fig. 1a) probably associated with occasional alpine lee cyclogenesis over the Gulf of Genoa and the summer Mistral. Other regions of strong winds include the strait of Bonifacio between Sardinia and Corsica (mean wind up to 7 ms^{-1}) and the north-west coast of Corsica. These features are seen both in QuikSCAT (Fig. 1a) and in COAMPS (Fig. 1b), and it is noteworthy that the COAMPS winds add more detail and finer structure and better resolve the Corsica/Sardinia Strait jet. (QuikSCAT data is assimilated into COAMPS, so the largescale structures should be similar.)

Transient variability of the winds can be seen in mooring data from LASIE07, from the ODAS buoy, (Fig. 3a, for locations see Fig. 1). In particular observed wind speeds approached 10m/s or more on the 26/27th June and 3rd /4th July , 23rd June, and 9th/10th July (Fig. 3a).

COAMPS model data at the closest grid point to the moorings (Fig. 3a, green and red lines) reproduces the main features of these wind events, but a close inspection reveals some differences. The overall correlation between the fully coupled model and observations at ODAS is 0.68 for the coupled model, for 3-hourly averages. The mean bias is rather small, around 0.5ms^{-1}, whilst the rms errors are around 2.4 ms^{-1} for both locations. The uncoupled run produces fairly similar wind speeds (Fig. 3a, red line) but has slightly lower correlation of 0.63.

Near surface air temperature and humidity, and turbulent heat fluxes

The sensible heat flux plot (Fig. 3b) shows that the COAMPS model often predicts large, positive (unstable) heat fluxes which are not shown at ODAS, for example in the morning of the days 16, 17, 26, 27, 28, 35. On these days the wind speed is reasonably high in the model (>5m/s, Fig. 3a) and the model air temperatures are too-cool (not shown), compared to ODAS. This, combined with the general tendency for COAMPS SST to be too high, leads to large sea-air temperature difference and the overlarge sensible heat fluxes. On other occasions model–ODAS differences are partly due to weak winds in the model (e.g. at the end of day 22 (Fig. 3a, when the observations show a large negative sensible heat flux not shown in the model (Fig. 3b)).

The latent heat flux plot (Fig. 3c) shows that the model has some skill in reproducing some of the large 150-200Wm^{-2} events that occur on the strong wind days of the 23rd, 26th, and early on the 4th July. On these days COAMPS slightly underpredicts relative humidity (not shown) and wind speed (Fig. 3a). The low air relative humidity in the model tends to cancel the effect of the low wind speed error on latent heat flux, so that the model and observed latent heat fluxes tend to agree on those days (Fig. 3c). On other days, agreement is not so good, and the overlarge latent heat fluxes in the model on the 16^{th}, 17^{th}, 27^{th} June and 5^{th} July are due to lower air humidities than observed and sometimes to larger wind speeds than observed (early on the 27^{th} June and on the 5^{th} July, Fig. 3a).

Despite the biases in sensible and latent heat flux, the correlation coefficient between model and observations are high: 0.53 for sensible and 0.62 for latent, significant at 99%. The corresponding correlations for the uncoupled run are 0.44 and 0.64 respectively.

IV. CASE STUDY OF A SUMMER MISTRAL EVENT

To study the air-sea interaction in the Ligurian Sea in more detail, a case study was performed for the Mistral wind period 26 June to 28 June. Here, we aim to fully understand the differences between an uncoupled and a coupled simulation. For this purpose, the experimental design for Section 3 is not optimal, because of the use of data assimilation every 12 hours, and also because the SST used for the atmosphere in the uncoupled run (the NCODA SST) has some general biases relative to the coupled run SST. So, instead we designed an experiment where the initial SST for both the coupled run and the uncoupled run is identical, and is set equal to the global NCOM field for 00Z 26^{th} June. The coupled run then proceeds for 3 days with 12-minute coupling in free mode (with no data assimilation after time zero), whilst the uncoupled run keeps the SST for the atmosphere fixed at its initial value for the whole 72 hours of the run. Hence, differences that arise in the two experiments are solely due to the coupling that occurs during the run, and not due to initial biases in the SST field.

The 3-day average wind speed and velocity at 10m for the 26^{th}-28^{th} June from QuikSCAT reveals the strong winds of 12 to 13ms^{-1} over the Ligurian Sea associated with the Mistral (Fig. 4a). The COAMPS winds are slightly weaker, but reproduce the main features of the flow (Fig. 4c). The magnitude of the wind speed difference, about 1ms^{-1}, is similar to that found in the timeseries data at ODAS during this period (Fig. 3a). As noted with respect to Fig. 1, the model adds more detail, for example resolving the Mistral and Tramontane winds in the Gulf of Lions, and the jet through the Strait of Bonifacio, and the corner jet around the northern coast of Corsica (Fig. 4c).

The ocean response to the winds is illustrated by the difference in SST between the 29^{th} June and the 26^{th} June, from the analysed infrared satellite SST data (Fig. 4b). The ocean cools by over 1°C over 72 hours in most of the Ligurian Sea and northern Tyrrhenian Sea, with the strongest cooling to the north and west of Corsica, and east of the strait of Bonifacio where the cooling is between 2°C and 3°C. Clearly, the strongest cooling occurs in the regions of strongest winds, with the exception of the western Gulf of Lion where there is weak warming. East of the Strait of Bionfacio, the cooling is reminiscent of the filaments identified by [12,13].

The coupled COAMPS model reproduces most of these details of the ocean response to the strong winds (Fig. 14d). It shows a cooling of over 2°C in parts of the Ligurian Sea and up to 3°C east of the strait. Noting that the atmospheric model of the uncoupled run does not see this SST change (the SST is kept fixed), we may expect a large difference in the fluxes between the two experiments. In particular, in the regions of cooling SST in the coupled run, a larger value of air-sea temperature difference T_a-T_s is likely, because of the reduction of T_s, (although some compensation may occur as the air temperature adjusts to the SST).

The surface latent heat flux averaged over the 3 day coupled run shows large fluxes over 200Wm^{-2} where the winds are strong (Fig. 5a), and the surface stress reaches up to 0.25Nm^{-2} in these regions (Fig. 5b). When taking the difference between coupled and uncoupled, the latent heat flux is reduced by up to 100Wm^{-2}, or 50% (Fig. 5c, contours) in the regions of strong SST cooling (Fig. 4d) and the stress reduced by up to 0.05Nm^{-2} or 20%. The sensible heat fluxes show similar differences up to 30 Wm^{-2} (not shown). The differences in heat fluxes are due to a combination of the change in stability between the experiments, directly affecting air-sea temperature difference and indirectly the turbulent exchange coefficients, as well as differences in wind speeds between the runs. Further, cooler SST in the coupled run would mean a smaller saturation specific humidity at that value of SST (q_{sat}(SST)), so the difference between air humidity and q_{sat}(SST) is likely to decrease, contributing to lower latent heat flux in the coupled run. A change in stability (i.e. air-sea temperature difference) of 1°C between the experiments is comparable to the magnitude of the actual air-sea temperature difference in the runs: thus leading to large potentially 100% changes in sensible heat flux. The wind speed differences reach up to +/-0.5ms^{-1} or about 5% of the average wind speed and are not likely to cause a large effect on the heat fluxes. In contrast, changes in the stress are more due to wind speed changes than to stability changes (the latter affects stress via the drag coefficient). At wind speeds of 10ms^{-1}, the effect of a 1°C change of stability on drag coefficient is fairly small, less than 10% (e.g. Liu et al. [14], their Fig. 12), whilst a wind speed change of 0.5ms^{-1} would create about a 10% change in stress.

When the reduced fluxes (heat flux, stress) in the coupled run act on and interact with the ocean model, the resultant cooling of SST is diminished, relative to the uncoupled simulation where the fluxes are not modified by changes in SST. In other words, the coupling provides a negative feedback on the surface forcing under strong winds.

V. CONCLUSIONS

The coupled COAMPS model has been validated against in situ and satellite data from the LASIE07 experiment in the Ligurian Sea (western Mediterranean) in the summer of 2007. Firstly, a month long simulation was performed, with data assimilation for the atmosphere, for a fully coupled case and an uncoupled case which used an analysis SST to compute bulk fluxes. Secondly, a short 3-day run was performed in non-assimilating mode to isolate the effects of coupling more clearly.

The fully coupled model performs well in the month-long simulation when compared against the observational data. The time-mean structure of the near-surface wind field compares well against QUIKSCAT satellite data, and adds enhanced detail to that seen by satellite. When compared against independent (non-assimilated) buoy data, the wind speeds correlate at 0.68 against a deep ocean station. The model slightly underpredicts wind speeds at the deep station.

Correlations between the model and observations for sensible heat fluxes and latent heat fluxes are 0.53 and 0.62 respectively, significant at 99%. The model tends to have large spikes in heat flux occurring in the daytime which often have no observed counterpart.

In the month-long assimilative run, the differences between coupled and uncoupled run are generally small. Some of this may be attributable to use of data assimilation in the atmosphere. For that reason a short, three-day, non-assimilating run was performed. Both the uncoupled and uncoupled run started with the same initial conditions and for the uncoupled run the SST was kept fixed at the initial value. The 3-day run encompassed a strong Mistral wind event that caused significant ocean surface cooling in both observations and model. The coupled response to the winds led to a significant reduction in surface stress (up to 20%) and latent heat flux (up to 50%) relative to the uncoupled run, in the areas of strongest cooling. This case study provides a clear example of the importance of coupling in synoptic events.

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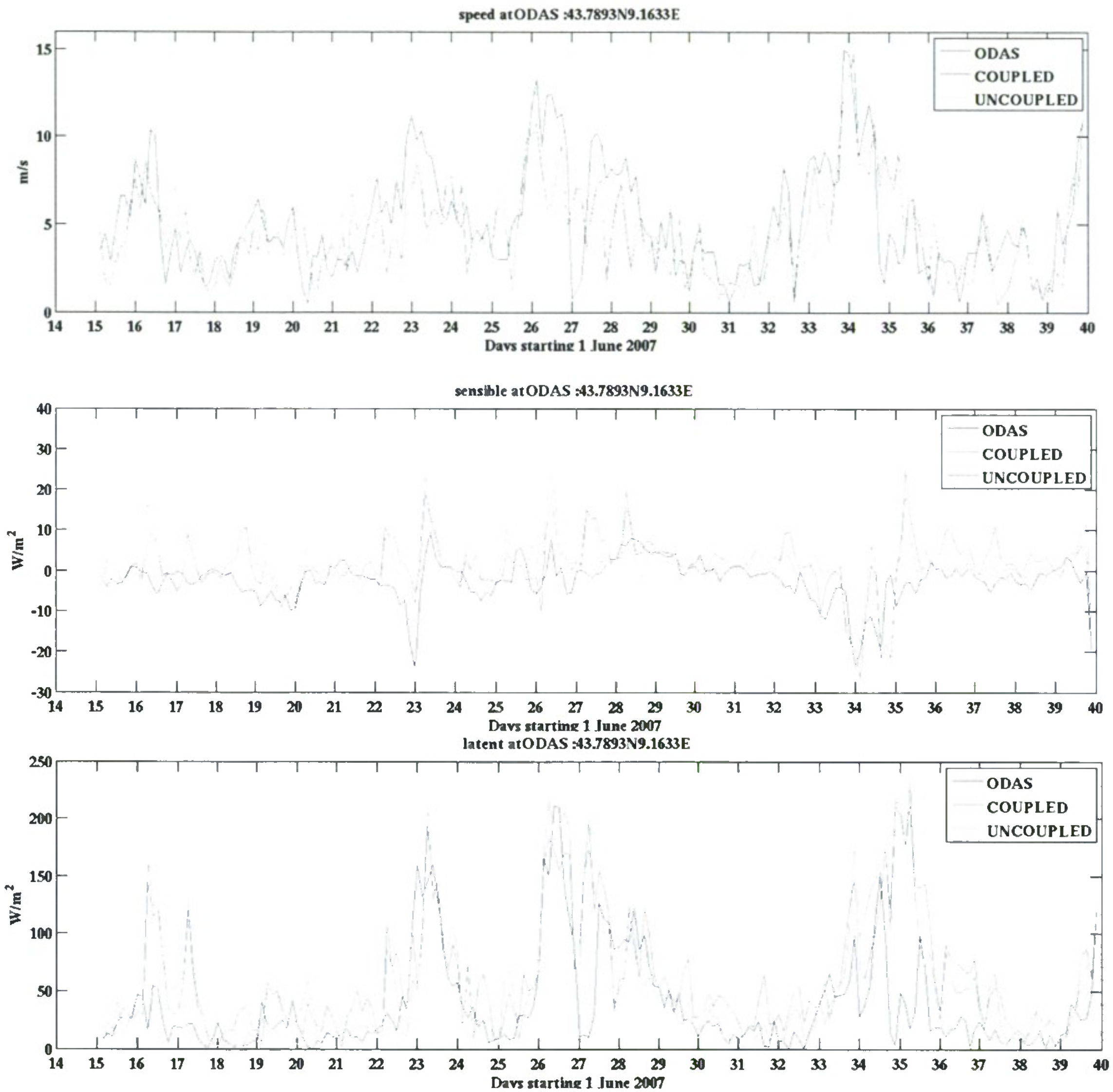

Figure 3. Top (a) Wind speed measurements from LASIE07 mooring data and from the COAMPS model. Observations from the ODAS buoy (blue): model data from the inner 4km grid, nearest grid point, 10m wind: coupled (green) and uncoupled (red). Data from 15th June to 9th July. Middle (b) – as a) but for sensible heat flux. Bottom (c) – as a) but for latent heat flux.

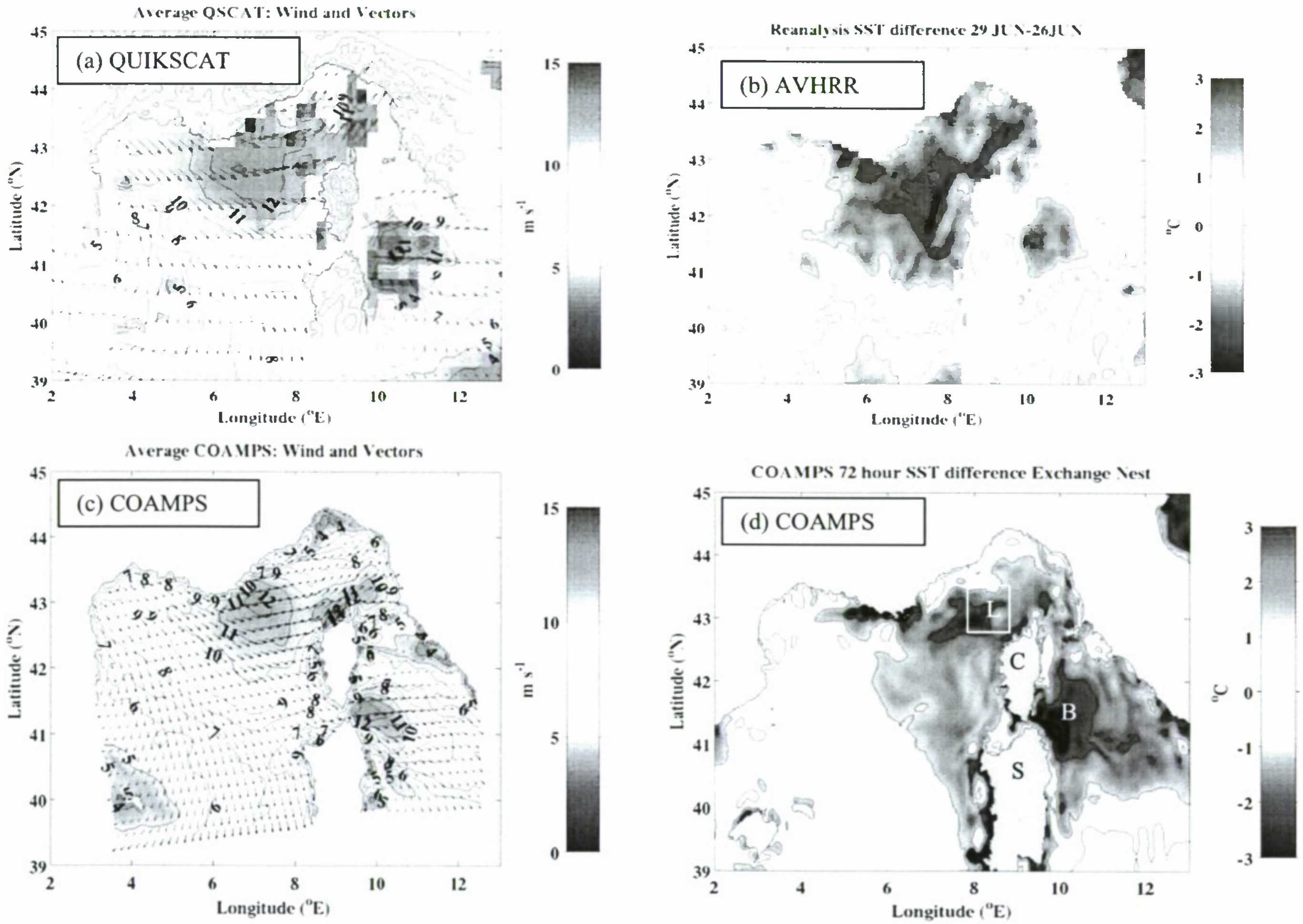

Figure 4. Mistral winds and ocean response during LASIE07. Left: 10 m wind speed and vectors, average 26 June to 29 June 2007 during Mistral winds. Right: SST change, 29thJune Figure minus 26th June. The top panels show observations, from QuikSCAT scatterometer, and from an optimally interpolated AVHRR composite (from GOS CNR data). The bottom panels show results from the COAMPS coupled model. The labels L, B, C and S at bottom right refer to Ligurian Sea, Strait of Bonifacio, Corsica and Sardinia respectively.

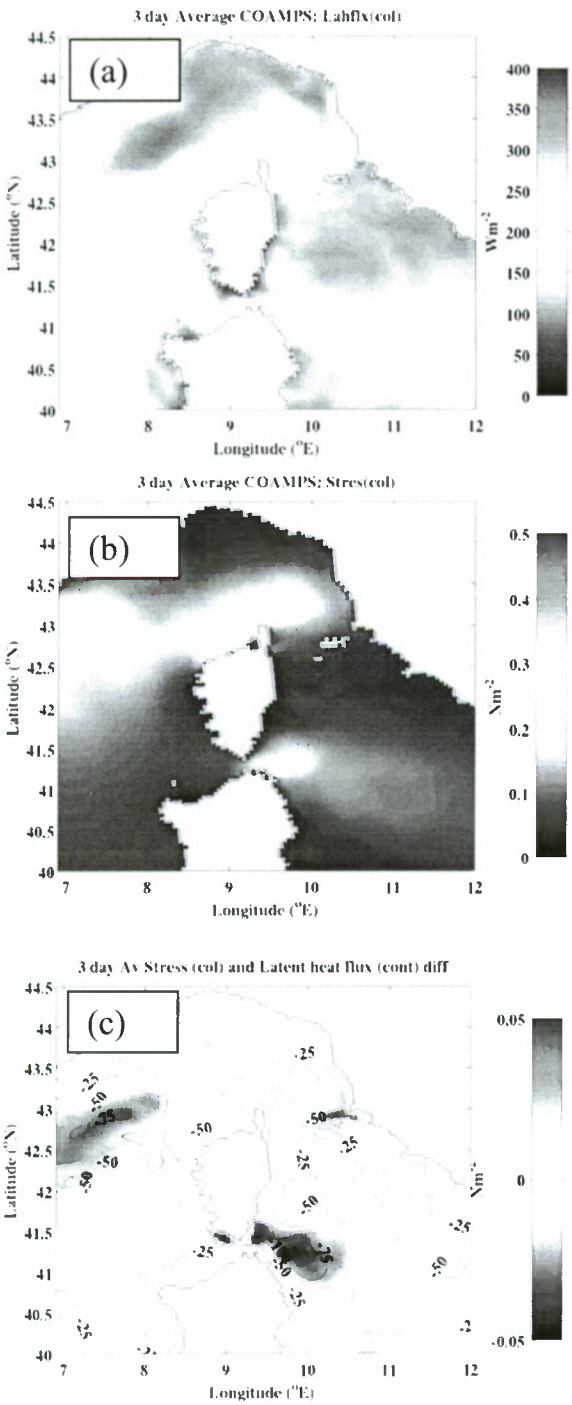

Figure 5. Three-day averages (26-28 June) from the coupled model of (a): surface latent heat flux Wm^{-2} and (b): surface stress Nm^{-2}. (c) shows the difference of 3-day average latent heat flux (contour) and stress (color) between the coupled run minus the uncoupled run.